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Soil macro- and microstructure as affected by different tillage systems and their effects on maize root growth

N. Dal Ferro [a,*], L. Sartori [b], G. Simonetti [a], A. Berti [a], F. Morari [a]

[a] Department of Agronomy, Food, Natural resources, Animals and Environment, Agripolis, University of Padova, Viale Dell'Università 16, 35020 Legnaro (Padova), Italy
[b] Department of Land, Environment, Agriculture and Forestry, Agripolis, University of Padova, Viale Dell'Università 16, 35020 Legnaro (Padova), Italy

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ABSTRACT

Tillage practices are critical factors for the sustainability of cropping systems by modifying the soil properties and affecting root growth. In this study we compared conventional (CT) and no tillage (NT) practices to evaluate their effects on soil structure and maize root morphology and dynamics during a two-year transition period. Pore size distribution and morphology-related parameters were analyzed with a combination of X-ray microtomography (microCT) (54–2250 μm) and mercury intrusion porosimetry (MIP) (0.0074–100 μm) within the 0–40 cm soil profile. The network model PoreXpert was applied to MIP pore distribution curves to identify subtle structural changes as affected by tillage. Root samples were collected down to 1-m depth with the core method during 2005 and 2006, 40 and 114 days after sowing, in order to quantify their mass, length and diameter. Results suggested that tillage practices affected the soil macroporosity (54–750 μm) while the micropores, detected with MIP, did not show significant differences between treatments. Conventional tillage, disrupting the macropore structure and enhancing the pore class in the range 54–250 μm, improved the soil loosening. Bulk density measurements, achieved in the last date (day 114, 2006), were negatively correlated with root growth indicators. Nevertheless, root growth was weakly affected by tillage since the soil structure did not reach a new architecture after the introduction of NT. In spite of the experiment being conducted in the short-term and the soil structure still being unpredictable, microCT analysis proved its ability to predict subtle structure changes as affected by conventional and no tillage practices.

1. Introduction

In the last decades, the conversion from conventional (CT) to no tillage (NT) practices has been widely endorsed worldwide, reaching up to 70% of the total cultivated area in South America (Derpsch and Friedrich, 2009). Despite the limited diffusion in Europe (Basch et al., 2008), conservation tillage has recently received growing interest due to its economic and environmental benefits, such as reduction of runoff and erosion, mitigation of phosphorus pollution, enhancement of soil organic carbon (SOC) sequestration, etc. (Soane et al., 2012). These authors argued that nowadays, after much research on conservative practices, the positive or negative response of soil structure to NT after its introduction might be predicted. An increased aggregate stability is generally recognized as a factor limiting the physical degradation, i.e., erosion and surface crusting (Le Bissonnais, 1996), promoting crop establishment and yield. Furthermore, increases in vertical macroporosity with no tillage (Holland, 2004), as a result of a larger number of elongated transmission pores (Pagliai et al., 2004), would improve air and water permeability throughout the soil profile. Increased soil bulk density (e.g. Munkholm et al., 2012a; Soane et al., 2012) and strength (i.e., penetration resistance) in NT systems would also positively affect the soil bearing capacity.

Conversely, by modifying the soil structure within the soil profile, no tillage would create a soil structure stratification that negatively affects root-growth and root-induced parameters (e.g. C distribution). NT generally enhances a more superficial root lateral development, limiting root penetration. The effect has been associated to excessive soil compaction (e.g. Munkholm et al., 2008), an altered distribution of the water content profile (Dwyer et al., 1996) or a suboptimal soil temperature due to the insulating effects of surface residues (Muñoz-Romero et al., 2012). Hindered root penetration and proliferation were observed in both winter (e.g. wheat; Munkholm et al., 2008) and summer crops (e.g. maize;

* Corresponding author. Tel.: +39 0498272886; fax: +39 0498272839.
E-mail address: nicola.dalferro@unipd.it (N. Dal Ferro).

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Ball-Coelho et al., 1998) as a consequence of excessive topsoil compaction. By modifying the pore size distribution, tillage practices generally change total porosity and bulk density although their effect would be time- and soil type-dependent (Kay and VandenBygaart, 2002). Nevertheless other authors (Ehlers et al., 2000; Aura, 1999) highlighted that the development of a system of continuous pores in NT (e.g. vertical biopores) could facilitate root vertical penetration, counteracting the negative effect of compaction. Dwyer et al. (1996) showed that maize rooting depth increased with tillage in a sandy loam soil, while soil water content significantly decreased. They hypothesized that higher soil moisture in the top 50 cm under NT reduced root exploration of the deeper soil layers compared to CT. Similar results were reported by Muñoz-Romero et al. (2012), who found that conventional tillage was more favorable than no tillage for chickpea root development, although they attributed the differences to a higher soil temperature in CT during the flowering and grain-filling stages. Accordingly, root morphological parameters (e.g. diameter, length density, etc.) can change drastically under no tillage as a consequence of soil structure changes above and below the tillage/seeding depth. By modifying the pore size distribution, soil compaction generally increases the soil mechanical impedance and decreases pore continuity, restricting the root length (Lipiec et al., 2012).

Exploring the soil structure through the pore network at both micro- (<50 μm) and macroscale (>50 μm) and the relationship with plant roots is of primary importance for understanding the ecological dynamics in the vadose zone. A detailed insight of the role of different tillage on root growth is still not completely known since adequate sampling depth and accurate information on pore and root morphology within undisturbed soil columns are rarely achieved (Muñoz-Romero et al., 2012; Chassot et al., 2001). X-ray computer assisted microtomography (microCT) has recently demonstrated considerable promise for non-destructive studies in the geosciences (Mees et al., 2003) at different scales (Dal Ferro et al., 2013). MicroCT scanners can achieve high resolution (in the order of few microns) in samples of representative volume (ca. 5 cm) and enhance image capability in terms of detecting subtle structure changes. The technique has demonstrated enormous potential for quantifying in situ root-soil interactions due both to their 3D complexity and ability to estimate their effects within undisturbed soil columns (Mooney et al., 2012). However microCT has a weak ability to distinguish between roots and pore phases within the soil columns since the attenuation density of roots is similar to that of soil pores. Only in some particular cases (e.g. surface layer of a grassland) roots have been easily visualized (Kuka et al., 2013) as a result of high root density.

The aim of this study was to determine the effects on soil structure and root growth dynamics through the soil profile during a 3-year conversion period from conventional to no tillage system. With a combination of soil structure measurements (mercury intrusion porosimetry and microCT) and root image analysis, we quantified total porosity, pore size distribution and morphology of undisturbed samples and investigated their effects on total root mass, diameter and length through the soil profile.

2. Materials and methods

2.1. Description of the experiment

The experiment was set up on a private farm in northeastern Italy on the Venice lagoon coast (45°24′ N, 12°9′ E; −2 m above sea level). The local climate is sub-humid with mean rainfall of 912 mm, yearly average temperature of 13 °C and evapotranspiration (ET_0) of 945 mm with a peak in July (5 mm d^{-1}). The soil is a sandy loam (sand 44%, silt 41%, clay 15%) Fluvi-Calcaric Cambisol (CMcf) (FAO-UNESCO, 1990) with an average SOC content of 7.7 g kg^{-1} within the soil profile (0–40 cm).

Experimental treatments were established in 2004 in order to compare conventional tillage (CT), which included a 35 cm depth plowing in autumn and seedbed preparation with a spring-tine harrow immediately before sowing at a depth of around 3 cm, versus no tillage (NT), consisting of direct sowing on untilled soil using a double-disk opener planter for seed deposition. Treatments were replicated twice on adjacent plots with an average surface area of ca. 1.3 ha (440 m long × 30 m wide per each plot). Plots were cropped with continuous rainfed maize (*Zea mays* L.), fertilized at a rate of 294 kg N ha^{-1} y^{-1}, 106 kg P_2O_5 ha^{-1} y^{-1} and 26 kg K_2O ha^{-1} y^{-1}. The crop residues were not removed in either tillage treatment. All plots had been subjected to conventional tillage before starting the experiment.

2.2. Soil sampling

To evaluate the effects of tillage practices on soil structure changes and root development, the soil layer was sampled in 6 random positions per treatment in 2005 and 2006. Prior to defining the sampling positions, baseline measurements of apparent soil electrical conductivity (EC_a) were conducted in order to assess the soil spatial variability. Soil EC_a did not show any spatial trend (Sartori, 2010), therefore sampling positions were selected randomly within the plots. For root analyses and bulk density, 6 undisturbed soil cores (3 per each plot) (diameter = 8 cm; height = 5 cm) were collected in the inter-row using a hand auger (Eijkelkamp, The Netherlands) on two different dates (40 and 114 days after sowing). At day 40 (corresponding to 7/8 leaves stage) the profile was sampled every 5-cm layer from the surface to 30 cm; at day 114 (corresponding to flowering stage) it was sampled every 10-cm layer from the surface to 100 cm. Soil samples were stored at −18 °C prior to root analyses. In 2006, at day 114, in 3 out of 6 positions undisturbed samples (diameter = 8 cm; height = 5 cm) were collected at three depths (0–10 cm; 10–20 cm; 20–40 cm) to perform texture and structure analyses. The number of samples were halved because of the long time required to perform the structure analyses. Soil cores were stored at 5 °C prior to physical and chemical analyses.

2.2.1. Root analysis

Soil samples were washed for 2 h in a 2% (w/v) oxalic acid solution. Soil particles were then separated in a hydraulic sieving-centrifugation device with 500 μm mesh size (Cahoon and Morton, 1961). Roots were further cleaned by water sedimentation of heavy particles for 2 min and stored in a 10% (v/v) ethanol solution at 4 °C. Root growth parameters were quantified as reported by Vamerali et al. (2003). For each root sample, a 300-DPI resolution (11.8 pixel mm^{-1}) black-and-white image was acquired by digital scanning. Roots were floated in a transparent tray of 3-mm thick plexiglass surrounded by a waterproof gasket, leaving a usable surface of 26.5 cm × 17.4 cm, filled with a 3-mm water layer to improve separation and spacing of roots from unwanted residues. Images were processed with KS 300 Rel 3.0. software (Carl Zeiss Vision GmbH, München, Germany). Root length was determined by the modified fiber length algorithm (FbL) (Vamerali et al., 2006):

$$\mathrm{FbL} = \frac{R_P + \sqrt{R_P^2 - 16R_A}}{4}, \quad (1)$$

where R_P and R_A are root perimeter and area respectively. A minimum object area (16 pixels) was adopted to reduce background noise. Image analysis allowed root quantification in terms of: (a) volumetric root length density (RLD), calculated by referring the root sample length to the soil volume; (b) mean root